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# THE SAGA OF TIDE MILLS

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**Abstract**—The paper covers, succinctly, the introduction and historical development of tide mills and their geographical distribution on the European Atlantic littoral (Great Britain, France, Spain and Portugal). Mills in the United States and Canada are reviewed briefly. The main factors which help to explain the distribution of tide mills, the different types of sites (estuaries, bays, wetlands, salt-pans, etc.) and the infrastructures and mechanical elements directly linked to their functioning (dykes, ponds, sluices, wheels) are all analysed and the, by no means insignificant, problems of conservation dealt with. The bibliographic references should prove a useful source for those wanting further information. © 1998 Published by Elsevier Science Ltd.

*Keywords*: tide mills, littoral, France, Great Britain, Portugal, Spain, Canada, USA.

## 1. INTRODUCTION

The use of the energy generated by tides [1] is an integral part of the history of the sea. After France built its sizeable tidal power plant on La Rance, near Saint Malo in Brittany, in 1966, and the former Soviet Union, China and Canada followed suit with smaller ones, a curtain fell on tidal energy harnessing schemes. Recent interest in sources of renewable energy has undoubtedly contributed to the present attention given to the forerunners of tidal power stations [2]. The historic value of tide mills is being recognised, perhaps buttressed by possibilities of reviving their use towards modern versions. Changing attitudes to industrial archaeology [3] and growing concern for our maritime architectural and environmental heritage have also influenced the present trend towards the study and conservation of these remains, proof of the ingenuity of our forebears.

Nevertheless, tide mills are still little known and the few which are not yet derelict are under considerable threat, whether passively, from sheer neglect, or actively from developers. Measures for their safe keeping are urgently required. It is also a rare heritage, if we compare their numbers to those of other types of mills. Brittany is a case in point. Here, there remain a mere 90 tide mills as compared to 3000 water mills and 5000 wind mills [4].

In Asturias, on the Cantabrian coast of Spain, an 18th century document records as many as 4529 water mills as against just a handful of tide mills [5]. Yet, many of these rare mills are crumbling and few of them have been restored (Fig. 1).

So far, their study on both sides of the Atlantic has been very uneven. In Britain, Rex Wailes published the first detailed study of the mills of England and Wales in 1941 [6]. A few years earlier, a brief paper on the mills of the Basque Country, showed incipient interest in France [7]. In Portugal, concern for tide mills goes back to the 1960s [8]. Nevertheless, the present concern for tide mills in the various European regions only goes back to the mid-seventies [9] and especially to the eighties. Thus, it was not until 1988 that Jean-Louis Boithias and Antoine de la Vernhe brought out their remarkable book on the mills of Brittany [10].

Currently scattered, often unpublished, data, thus giving an overall view, both past and present, of Atlantic tide mills. After a look at the origin and historical development of tide mills on the European Atlantic littoral (France, Great Britain, Portugal and Spain), mills on the East coast of North America (Canada and USA) are also reviewed briefly. The second section deals with geographic distribution and its main factors, the different types of sites (estuaries, bays, wetlands, salt-pans, etc.) and the infrastructures directly linked to functioning tidal mills (dykes, ponds) are analysed. Although architectural and mechanical elements (sluices, wheels) characteristic of tide mills are also reviewed, milling techniques, common to all mills (wind, water and tide) are not dealt with here. Finally, the authors look at the present, rather sorry, state of most tide mills and summarise some of the more interesting attempts at conservation.

## 2. ORIGIN AND HISTORICAL DEVELOPMENT OF TIDE MILLS

### *Classical times*

The Greeks attempted to harness tides in the Euripus. Near Chalcis (Island of Euboea) and in Cephalonia (near Agostoli) tide mills provided energy. In the first century mills were in use in Asia Minor and Denmark. Some mills used tidal currents, and they are basically similar to river water mills. Undershot wheels, already in use during Roman times, were used on the floating tide mills on the Danube River. Such mills were still working below the Iron Gates in 1970. The first waterwheels may well have been put to work by the Persians by 200 BP. (Figs 2 and 3).

It was not unusual for tidal rivers to have tide mills near cities in medieval Europe. History has recorded that the Byzantine general Belisarius placed several of them on the Tiber River, near Rome, to provide the power to make bread for the besieged city. For such river tide mills two systems had been designed : the mill had either a single wheel which rotated, with the tidal current, between two pontoons, or there was a single pontoon with a wheel on each side, as is done with paddle-wheelers.

### *The Middle Ages*

It is for the Persian Gulf that tide mills are first mentioned. In the 10th century Arab geographer, Al-Magdisi Shams al-Din, described the mills found at Bassora (Irak), on the Tigris–Euphrates delta, explaining how water turned the wheels as it flowed back to the sea [11].

Water mills, and sensu largo, tide mills are already mentioned in Vitruvius' *De Architectura* (20 to 11 BP).

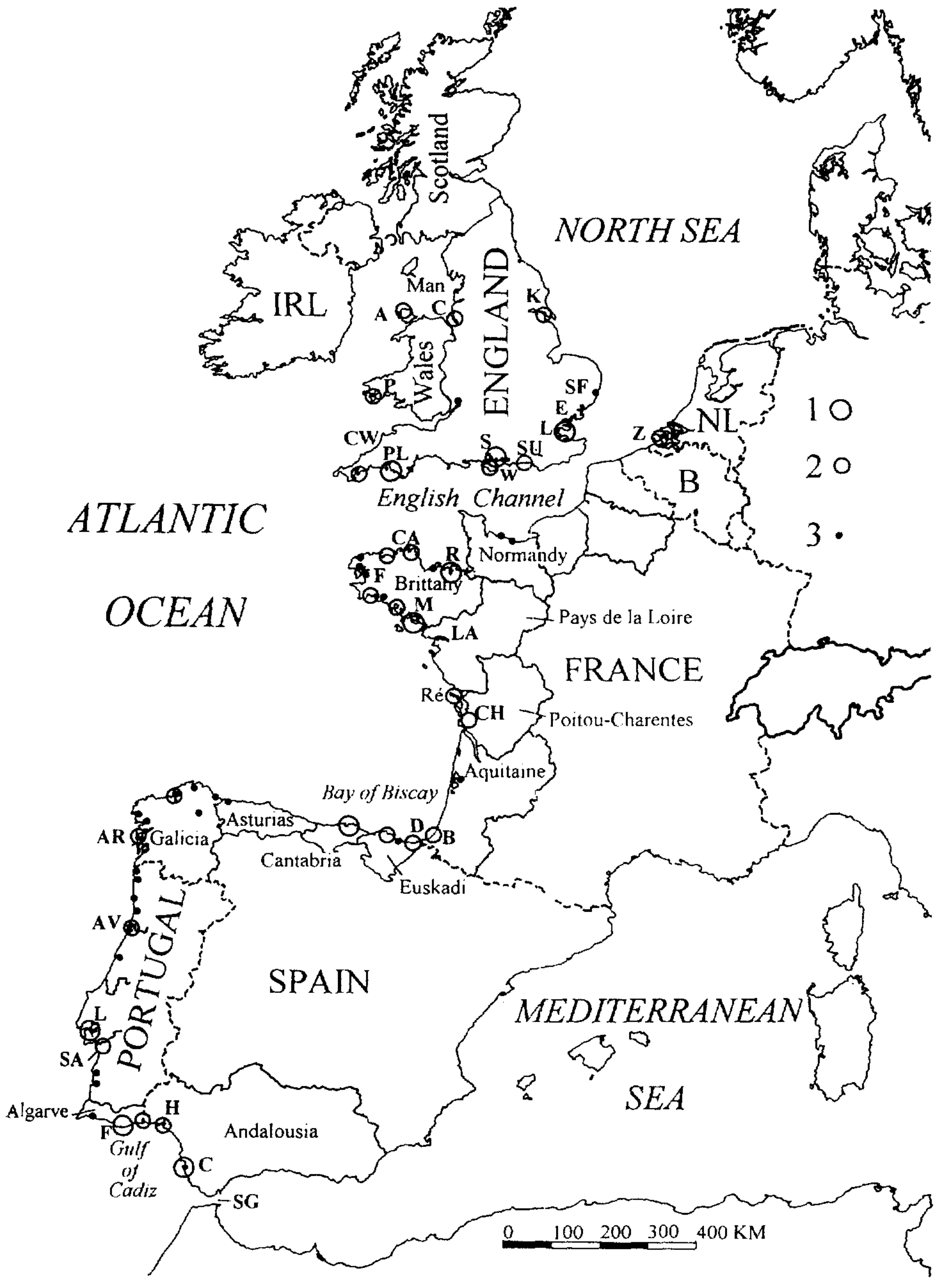


Fig. 1. Distribution of tide mills on the European Atlantic littoral. 1. High concentration; 2. Medium concentration; 3. Isolated mills. ABBREVIATION: IRL, Ireland; GREAT BRITAIN: A, Anglesey; C, Cheshire; CW, Cornwall; E, Essex; K, Kingston; L, London; P, Pembroke; PL, Plymouth; S, Southampton (Hampshire); SF, Suffolk; SU, Sussex; W, island of Wight. NETHERLANDS (NL); Z, Zeeland. FRANCE: B, Bayonne (Pyrénées-Atlantiques, French Basque Country): CA, Côtes d'Armor; CH, Charente-Maritime; F, Finistère; LA, Loire-Atlantique; M, Golfe du Morbihan (Morbihan); R, Rance estuary (Ile-et-Vilaine). SPAIN: AR, Ría de Arousa; D, Donostía or San Sebastián (Euskadi, Spanish Basque Country), CA; Cadiz; H, Huelva. PORTUGAL: AV, Aveiro; L, Lisbon and Tagus estuary; SA, Sado estuary. SG, Straits of Gibraltar.

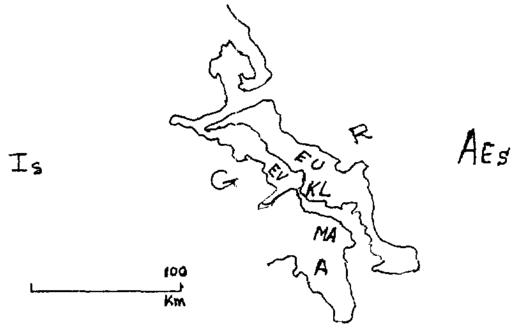


Fig. 2. Sites location in Greece.

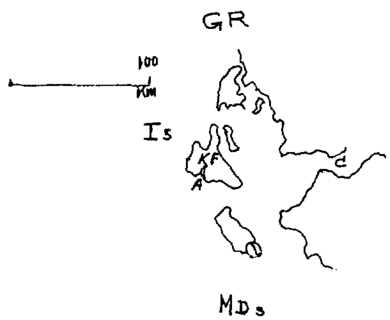


Fig. 3. Sites location in Greece.

Tide mills were mentioned in the *Domesday Book* (Dover) and in Richard Carew's *Survey of Cornwall*. The earliest known European mill was built in southern England between 1066 and 1086 at the entrance to the port of Dover [12]. In the 12th century other mills began to appear along the Atlantic coast from Britain to the Basque Country. Except for the Wooton Mill (Hampshire), dating from 1132, tide mills in England were built along the North Sea littoral: Bromley-by-Bow and Woodbridge (Suffolk) in 1135 and 1170, or Baynard's Castle near London in 1180.

Birdham Mill (built in 1768), St Osyth Creek Mill (1491), Quay Mill (1740), Stambridge Mill (1600s), Wootton Bridge Mill (Wight), Hayle Mill (Cornwall) are as many of the mills well described in documents; several of them kept working until the thirties and forties. London Bridge tide mills and the East Greenwich Mill used double effect generation.

Mills were used for grinding corn, rasping and dyeing woods and tobacco stem manufacturing.

Pembrokeshire had many mills some constructed by Flemings who settled there, others apparently by Frenchmen.

On the other side of the Channel, in Normandy, Richard I, the Lion-hearted, donated a mill in the Bay of Mont Saint-Michel to the Abbey of the same name while he was Duke of Normandy (1189–1199). A little further to the West, on the northern coast of Brittany, the Lupin mill, in the Rotheneuf Creek, is mentioned as far back as 1181. On the southern Breton coast, the Pencastel Mill at Arzon (Morbihan) was established in 1186 and is contemporary with the mill once found at Mesquer (Loire Atlantique), first mentioned in 1182 [13] (Fig. 4).

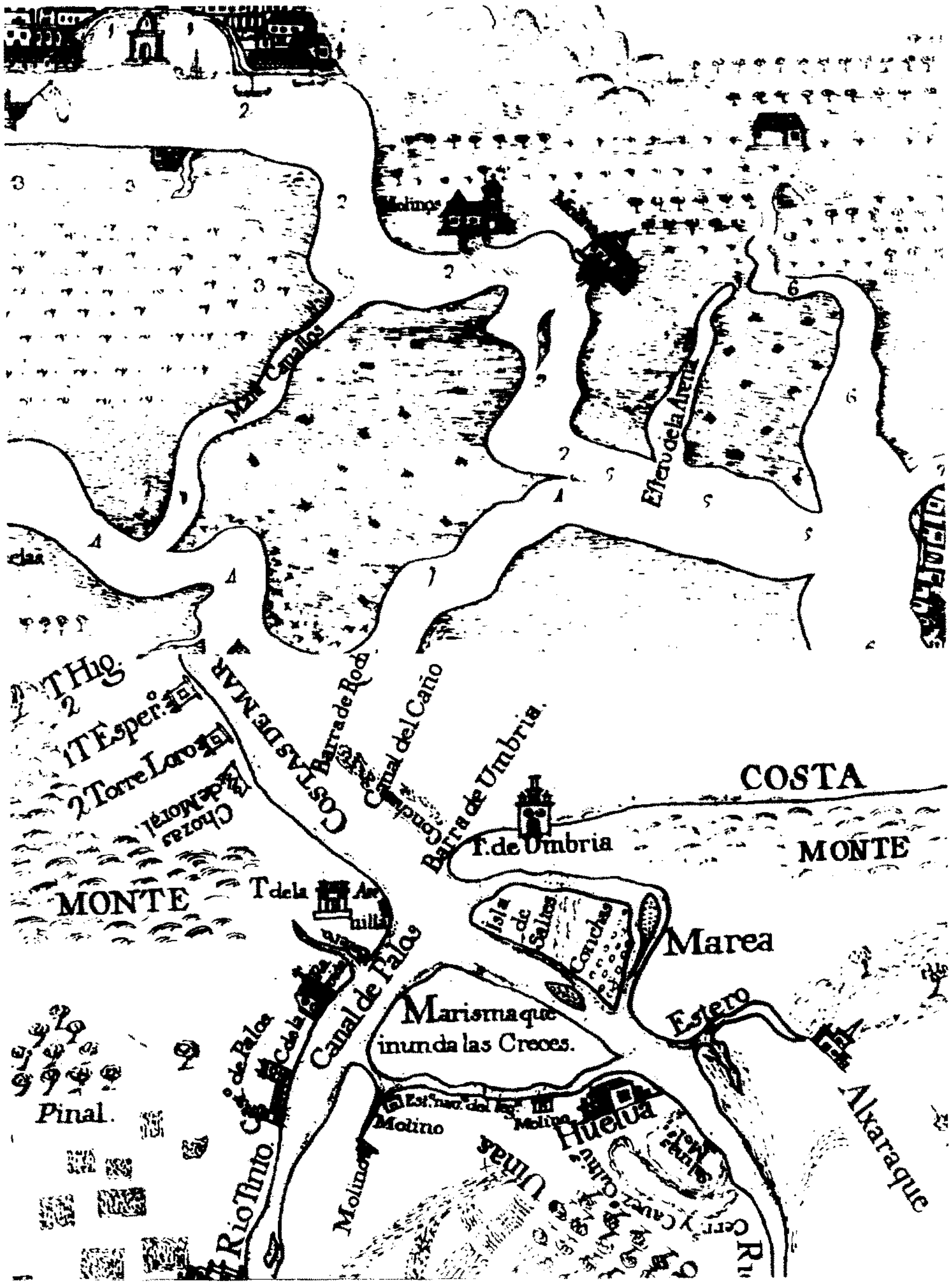


Fig. 4. Representation of four mills (Molino, Mol.) near the city of Huelva (Andalousia, Spain) on a map dating from the last third of the 18th century accompanying an address by Juan de Mora Negro (Arch. Munic. Sevilla). To the right (the uppermost part of the map points South), the port of Palos from which Christopher Columbus sailed on his historic voyage of discovery on 3rd August 1492. "Marisma que inunda las creces" : marshes flooded at high tide ; "Estero" : tidal channel ; "Conchas" : sea shells.

South of the Loire, on the Charentais littoral [14] the mills of St Nicolas and Pont de Maubec at La Rochelle, granted to the Knights Templar by Eleanor of Aquitaine in 1139, also deserve a mention. By 1300 there were seven mills along the Maubec canal in La Rochelle. Finally, in the French Basque Country, several mills were built in the first quarter of the 12th century including those of Bayonne, between 1120 and 1125 and that of La Mufale between 1123 and 1133 [15]. The Mategelos Mill is mentioned as early as 1187.

From the 13th century on mills were not only built along the East coast of England, Wooton having been the exception, but also along the southern coast at Southampton, Plymouth and on the Isle of Wight and even to the West in Wales, along the Severn estuary. Fifteen new mills were added in the course of that century [16]. Indeed, the number of mills seems to have increased steadily throughout the Middle Ages. According to Holt [17] there were 37 mills at work in England alone by 1300. Thereafter, sea mills as they were then called (the designation "tide" being relatively recent) were infrequently built. Wind mills were preferred because sea mills were occasionally damaged, even destroyed, by storms [18]. Thus, in 1299 the Milton Hall Mill (Essex) was replaced by a windmill and one of England's earliest tide mills, Walton Mill, reputedly in existence in 1086, was abandoned in 1300. Lynn Mill was wrecked by the sea in 1369, as had already happened to Gulpelar and Lestanton mills, both on the Deben River estuary.

Illustrations of such mills are found in Wailes [6] and Holt [17] provides pictures of Ashlett Creek Mill (Hampshire), the Beaulieu's sluice gates, Veranzio's floating mill design, and so on [63].

In The Netherlands the earliest known mill was built at Zuicksee in 1220. In France, the mill of Veulves (Normandy) was built in 1235 and those of l'Esbouc and la Nive (Basque Country) in 1251 and 1266. As far as the Iberian Peninsula is concerned, in the light of existing research, the earliest mill would appear to be that of Castro Marim, built below the castle, on the right bank of the mouth of the Guadiana River. This mill is represented on a manuscript drawing of the fortress of Castro Marim in 1290 [19]. Most of the early mills along the Cantabrian, Galician and Portuguese coasts appear to date from the 14th century, like the mill at Alcantara on the Tagus estuary built in 1313. The Corroios mill, near Lisbon, was built in 1403 by D. Nuno Alvarez Pereira [20] about a quarter of a century after that of Grand Traouiéros (N. Brittany) which dates from 1375.

This list is necessarily far from comprehensive, given the lacunae which still subsist in our knowledge of the history of tide mills. We should add that mills which have long since disappeared could well have been built prior to the 14th century on the affluents bordering the southern banks of the Loire estuary such as those of Vertou, on the Sèvre near Nantes, near Vue on the Tenue and in the Pays de Retz on the Acheneau [21].

In the 14th and 15th centuries, new mills were built in Britain, especially near Plymouth and Southampton. In the 15th century, three mills are mentioned in Lorient (Morbihan, France), another at Courseulles-sur-Mer (Normandy, France) and, according to a document dating from 1449, there was a tide mill on the Ría de Aveiro (Portugal) [22]. Several mills are also mentioned in Moguer, on the Tinto estuary (S. Spain) in 1436 [23] (Fig. 5).

### *From* 1492 *to the end of the* 18*th Century*

The Great Voyages of the 15th century, and especially the discovery of America by Columbus in 1492, undoubtedly affected the evolution of tide mills in the following century, especially in the proximity of major ports such as Lisbon or Cadiz. Across the estuary from the city of Lisbon, in the Vale-do-Zebro alone, there were 27 mills. They supplied an

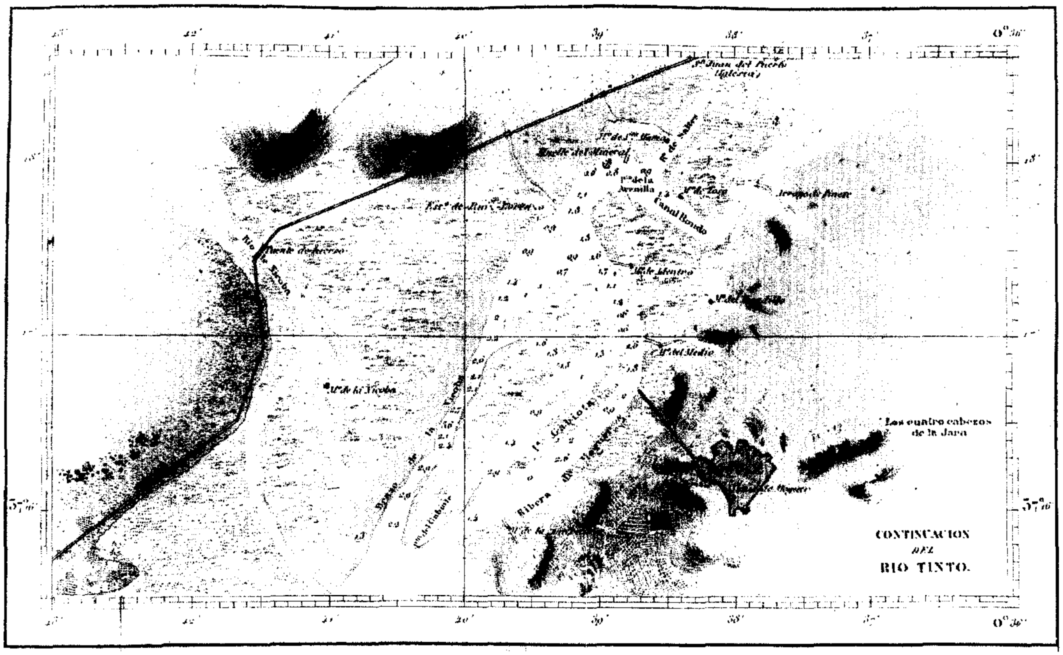


Fig. 5. Archive map of the Rio Tinto area.

equal number of ovens which produced ship's biscuits for the huge Portuguese Navy [24]. According to some sources there were about a hundred mills in the Tagus estuary and in its tidal creeks at the peak of activity in the port of Lisbon. In Spain, the first known drawing of a tide mill dates from this period: the mill, drawn by Francisco Lobato, was built at Puerto Real, a port city in the Bay of Cadiz, founded by the Catholic Monarchs in 1484 [25]. Several mills in Cantabria (N. Spain), such as those of Joyel, Fontorilla, Victoria and Barbijo, go back to the 16th century [26] (Figs 6 and 7).

In eastern Flanders, at the confluence of the Rupel and the Scheldt rivers, the Rupelmonde Mill (approximately between St Nicolas and Antwerp) probably dates from the early 16th century and was altered in 1567. In 1587 another mill was built at Zwijndrecht at 80 km from the mouth of the Scheldt River. In 1515, monks established the Birlot Mill on the island of Bréhat (Côtes d'Armor, N. Brittany). In the Spanish Basque Country, the Maria "errota" mill at Lequeitio is mentioned in 1555.

In the 17th and 18th centuries the growth in the number of tide mills along the Atlantic coast was accelerated by the development of grain crops and the colonisation of America. Some sixty new mills were established in Great Britain at this time [27]. Many of the mills in the Iberian peninsula also date from this period. In Cantabria their establishment was the consequence of the new road linking this northern region to that of Castille, thus allowing the export of flour to America from the port of Santander. By 1753, the year in which the La Venera mill was completed, fifteen mills, moving a total of 51 hydraulic wheels, had been built in and around Santander [28]. At the same time, the considerable development of salt-pans led to the establishment of several new mills in the course of the 18th century, as was also the case in the Bay of Cadiz, in Southern Spain [29] (Figs 8 and 9).

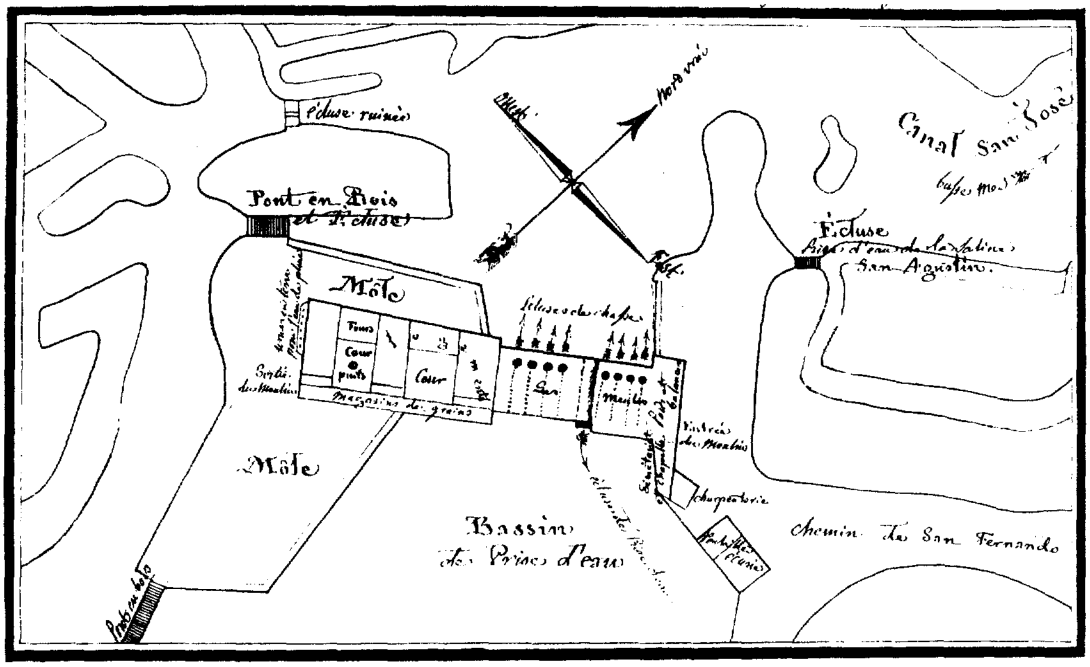


Fig. 6. Archive map of the San Jose location on the Bay of Cadix (1823).

In the French Basque Country (Pyrénées-Atlantiques), half the mills date from the 17th and 18th centuries [30]. In 1601 two mills were built on the southern bank of the Adour, near the confluence of the Nive. A mill was also built within the harbour of Ascain on the Nivelle. On the other side of the Pyrenees, in the Spanish Basque Country, most mills were built in the 18th century, including those of Ozollo "errota" and Maiukitza "errota" (1796).

It was in 1613 that the French, aided by the Micmac Indians, built the first tide mill in North America. This double function mill was to be found at Port Royal, capital of Acadia (now Annapolis Royal in Nova Scotia). This rich fishing area was colonised, in the early 17th century, by settlers from around La Rochelle and Brouage, famous for its salt pans. The early Acadian system of dykes, salt pans and the use of the marshes dates from this period [31]. Other mills soon followed in New England, notably at Salem in 1635 and at Boston [32] on the river Charles, though it was in the following century that Massachusetts saw a real increase in the number of its mills.

In Chelsea, Slade's Spice Mill was built in 1734, while others saw the day in Rhode Island and on Passamaquoddy Bay (2 mills). On Long Island, New York, [33] between 1793 and 1797, Abraham Van Wyck built a mill at Mill Cove Pond, near Huntington, which is now known as the Van Wyck-Lefferts Tide Mill [34].

Any reference to the 18th century would be incomplete without mentioning the Perse mill built in the city of Dunkerque (Dunkirk) (N. France) between two canals and described by Forest de Bélidor in his famous "Traité d'architecture hydraulique" [35]. This mill, almost certainly built towards the end of the 17th century and abandoned in 1714, was connected to a wind mill and its hydraulic system was a model of ingenuity allowing the miller to use both the incoming and the outgoing tides, a forerunner thus of the double effect tidal power plant. The 18th century also saw the establishment of more complex

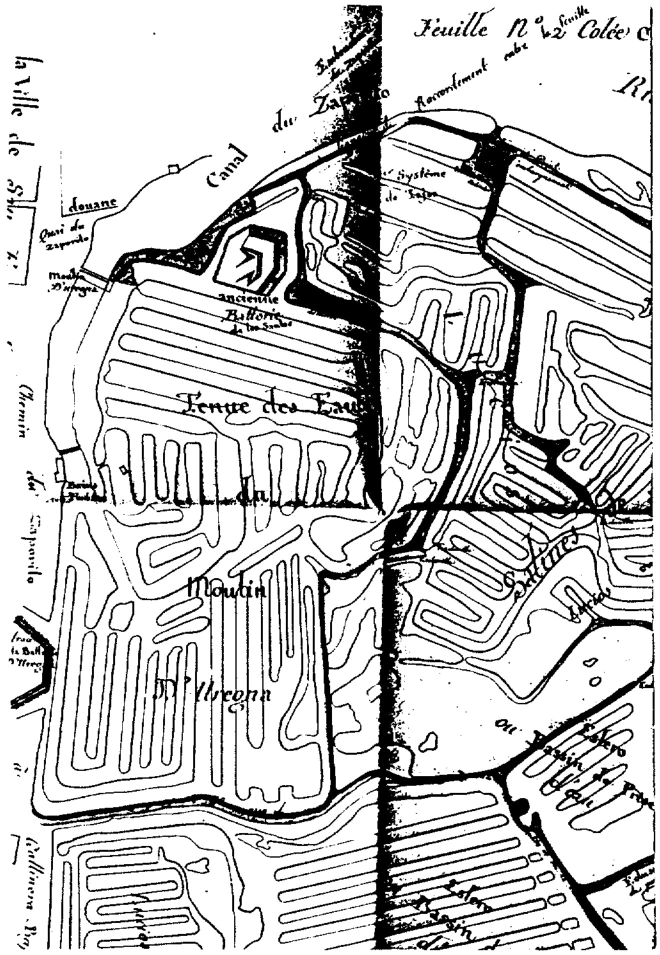

Fig. 7. French military map of the Bay of Cadix (Cadiz) (1823).

installations using tidal energy. Let us cite just two French examples. The first is an industrial flour mill with a two-way function, similar to the Perse mill, built in Bordeaux (1787–1788) on the present Bacalan quay. This monument of industrial architecture was described by numerous travellers, including Arthur Young, who were much impressed by the sheer size of the construction (65 × 29 m ; ±214 × 95 ft) and of the installations (4.8 ha ; 108 acres) [36]. The second example, the Indret Mill, situated at Basse-Indre (Loire-Atlantique) on an island in the Loire, housed an iron foundry. It was part of a never completed project of the French Manufacture Royale just before the French Revolution. The English engineer William Wilkinson, entrusted with the project, decided to use tidal power for the melting and boring of cannon. The plant functioned entirely on tidal power from 1778 to 1786 [37]. In Portsmouth (U.K.), between 1690 and 1704, the arsenal pumps functioned on tidal power. The mill in the arsenal of El Ferrol (Galicia), designed by Julián Sánchez Bort, of which a 1765 plan exists, had four vertical wheels, similar to Bélidor's, allowing the miller to take advantage of both the in-coming and the out-going tides [38]. In Spain and Portugal, in the 18th century, there were mills which, due to their size and the

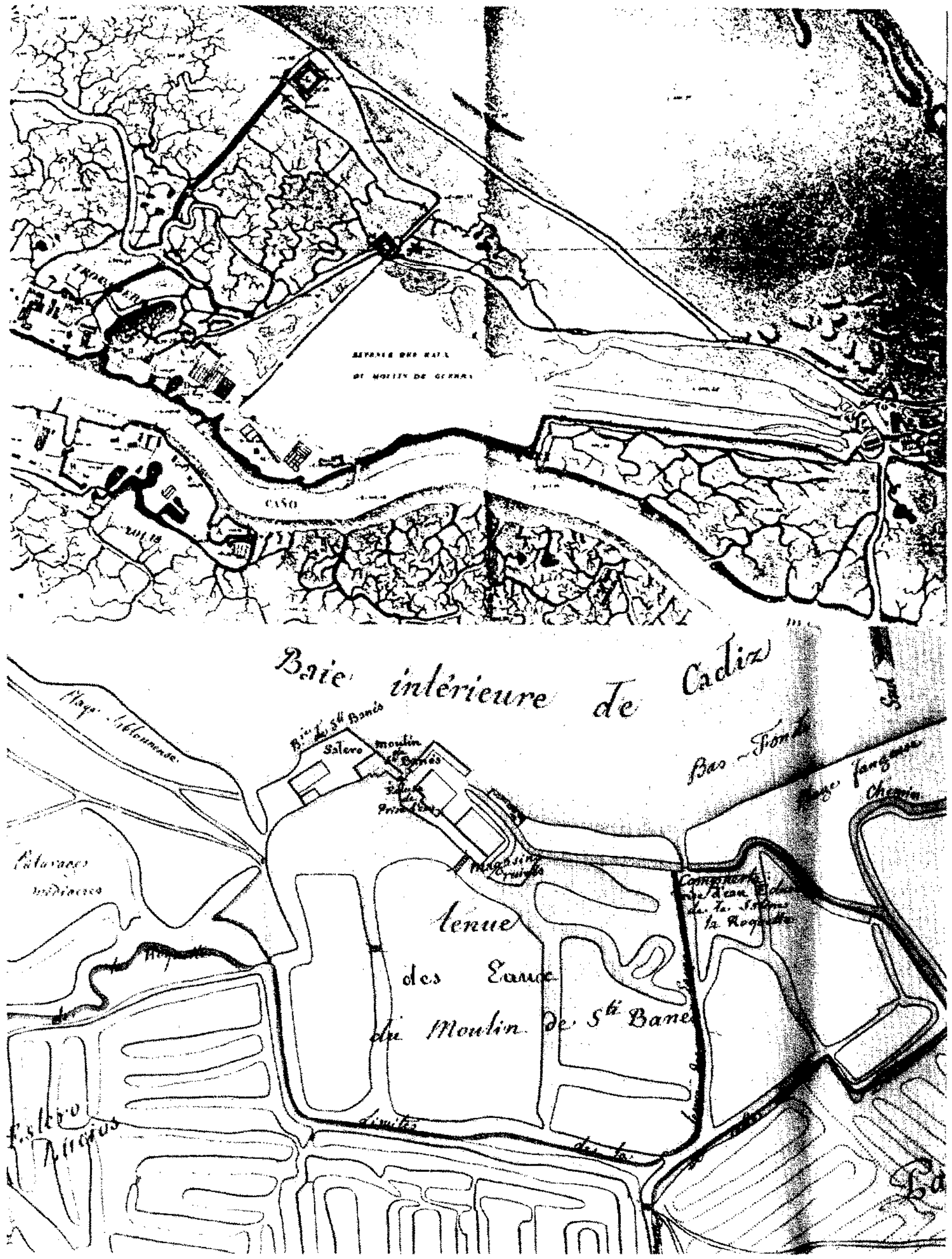


Fig. 8. Bay of Cadix (Cadiz) St Banes tide mill (1823).

number of their wheels, can be regarded as prototypes for the large industrial-type mills to be found in Northern Europe in the latter half of the 19th century (e.g. El Arillo in the Bay of Cadiz, Mondego in Portugal) (Fig. 10). In France, after the Revolution in 1789, when people were no longer obliged to take their grain to the local big landowner's mill, there was a significant increase in the number of tide mills.

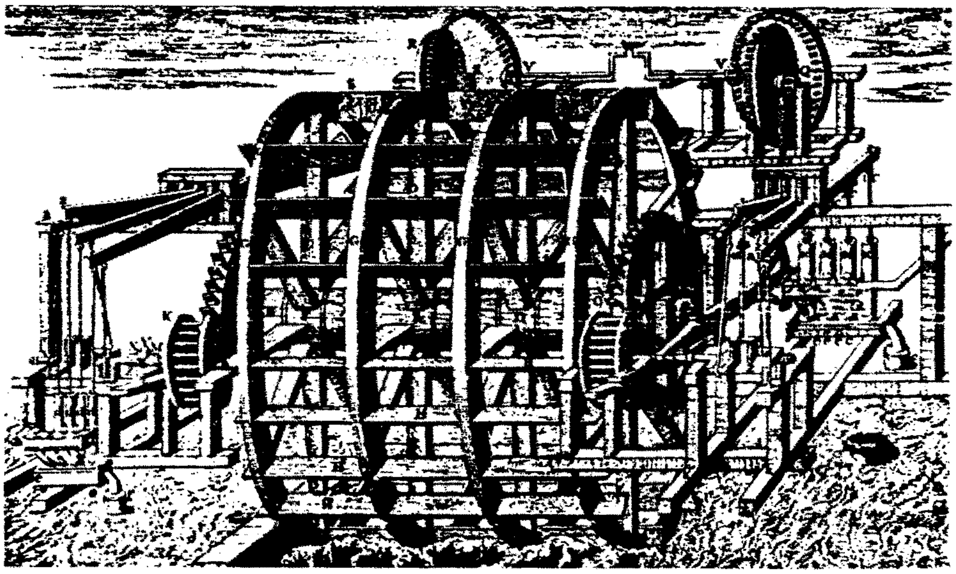

Fig. 9. Tidal mill machinery (engraving, 1703).

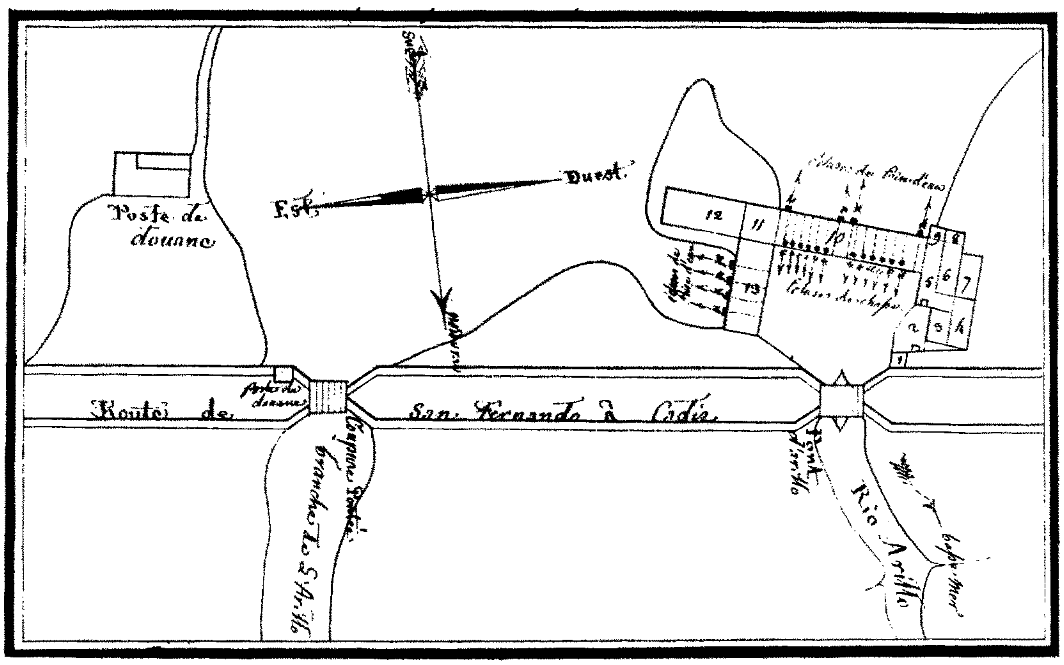


Fig. 10(a). The Arillo Mill in Cadiz. Water flowed into the pond through eight sluices perpendicular to the mill; it flowed back to the sea through twelve other gates which operated twelve horizontal wheels. Detail of a manuscript plan drawn by French engineers in 1826 (Serv. Hist. Armée de Terre, Vincennes, France).

Tide mills were still found 40 years ago in Suffolk, Sussex, Essex, Hampshire, Pembrokeshire, even London and the Isle of Wight. An East London mill stood on an embank-


Fig. 10(b). Right wing of Arillo Mill facing the sea.

Fig. 10(c). Cadiz. Arillo tide-mill at flood tide (Ph. L. Ménanteau).

ment, in the 17th century, and is on record as being the cause of flooding of Princes Meadows in the 16th and 17th centuries [66].

There were tide mills in Russia, in the 18th century, in Italy in the 19th, and near the Hanseatic city of Hamburg tidal power was used as late as 1880 to pump sewage.

*The 19th and 20th centuries: industrialisation and abandon*

The 19th century was to be marked by the Industrial Revolution which had already made considerable headway in the previous century. Nevertheless, straightforward, traditional

mills continued to be built in the first half of the last century and even later, e.g. the mills of Buguélès and Penvenan (Côtes d'Armor), towards 1820, or Lézardieux, on the estuary of the Trieux (Côtes d'Armor) in 1827. One of the last mills to be built was probably O Muiño do Mar (1905–1910), in the Ría de Ortigueira (Galicia, N.W. Spain) [39].

At the same time other mills either disappeared or gave way to "industrial" ones. Just as wind mills had often displaced tide mills in the past, steam, and later electricity, gradually superseded, or complemented, tidal power as they could guarantee an uninterrupted source of energy (e.g. the mills of Guinard or Beuzais on the Rance estuary or Folgoat in Finistère). Thus, turbines gradually took the place of hydraulic wheels (e.g. the Moulin de la Motte, in Côtes d'Armor in 1925). This trend continued in the late 19th century and was even more marked in the early part of the 20th century. Large mills on several floors, often turned into industrial flour mills (e.g. Pont Canada on the Jaudy and Pont l'Abbé by the castle, Côtes d'Armor) either replaced the early mills or were built next to them (e.g. Kendreuff on the other side of the dyke).

Around 1900, some 30 mills still functioned on the Tagus estuary near Lisbon. The example of Brittany, which has been well studied [40] illustrates fairly clearly how activity gradually peetered out. Several mills were abandoned between the two World Wars: La Fosse-Mort (in 1930) in Ile-et-Vilaine, Birlot (1916), Grand Trauoiéros (1919) and Pleumeur-Bodou (1928) in the department of Côtes d'Armor, Campen (c. 1920), Ludré (1925–1930) and Noyalo (1930) in Morbihan. Due to the privations suffered throughout Europe during the early forties many continued to function during the Second World War and ceased to do so either immediately after the war, or in the early fifties, like those of Lézardieux (1945) and Dourduff-en-Terre (1950) in Côtes d'Armor, Moulin-Mer (1947) in Finistère, le Hézo (1952–1953) and Le Kerlioret (1952) in Morbihan. Finally, a few continued to function until the sixties and even the seventies: Beringue and Pomper (1960), Traou-Meur (1961), Pont-de-Cieux (1964), and Mériadec (1965–1967). Transformed flour mills using fuel or electricity resisted somewhat longer as was the case of mills along the Rance, notably La Cale (1970) and Bauchet, which closed down as late as 1980.

In Britain the first half of the twentieth century saw the closure of numerous mills [41]. In Hampshire, Quay Mill, built around 1740, stopped working in 1920, but remains a picturesque historical landmark. No fewer than 23 mills were still in existence, at the end of 1940 in England and Wales when Rex Wailes published his study [6]. Several mills closed down in the 1930s, but ten of them were still functioning at the beginning of the Second World War. The mill at the head of St Osyth Creek in Essex, built by the Abbey before 1491 and restored in 1730, closed down in 1930 and had disappeared by 1940. Birdham Mill, at the mouth of the Chichester Canal, in Sussex closed in 1935 and Fingringhoe a few months after the beginning of the war. Slipper Mill, near Emsworth, repaired in 1735, and probably also in the 1930s, was fully operational on the eve of World War II, as were Wootton Bridge, on the Isle of Wight and the 300-year-old Stambridge Mill, on the river Roach, near Rochford.

By 1950 only a handful of mills still functioned in Suffolk, Essex, Sussex, London, Hampshire, the Isle of Wight and Pembrokeshire. None of the Anglesey mills appear to have functioned in this century, and little remains of the once numerous Cornish mills. Only the foundations of Hayle Mill, a four-storey stone building, are still visible [42].

For Spain, a few mill-closure dates are also known. In the Bay of Cadiz, the large mill of El Arillo (or Molino de Méndez) ceased activity at the beginning of the Spanish Civil War, in 1936. In Galicia, in the North West, O Muiño do Mar, in the Ría de Ortigueira

ceased to operate in the 1940s partly as a result of the construction of the railway, and As Aceñas de Verxelles, on the Ría de Viveiro, stopped working as late as 1955–1960 [43] (Fig. 1).

In Portugal, the situation was no better. Only four mills, Corroios on the Tagus and Marinhas on the Sado estuaries, as well as two mills known as Moinho da Asneira near Vila Nova de Milfontes, were still working in the sixties.

## 3. GEOGRAPHICAL DISTRIBUTION OF TIDE MILLS

To understand the extent to which tidal energy was used, one may first look at the geographical distribution of tide mills. Given the lack of data available for certain countries, however, the figures are, at best, approximate. Furthermore, this distribution does not take into account either the type of mill or its construction date, let alone the fact that many have since disappeared. In all, over 800 mills were built on both sides of the Atlantic and the North Sea, and over half of these were to be found on the European littoral.

*Europe*

From Scotland to the Straits of Gibraltar, Great Britain, France, Spain and Portugal once totalled some 500 mills! A closer look at their distribution, with particular attention to the areas of highest density, might prove informative (Fig. 1).

*Great Britain*

Of the 140 mills once found in Great Britain many were along the North Sea coast, site of the earliest mills, and on the Thames estuary (e.g. Kingston). Along the southern coast, the highest density was to be observed near the major ports, such as Southampton [44], Plymouth and Portsmouth, and on the Isle of Wight, where the Bembridge Mill was described by the grandson of the naturalist, Charles Darwin. In the West, St George's canal, the Severn estuary (Wales), Pembroke Bay and the Isle of Man all had their fair share of mills. In fact, right along the British coasts, not omitting Northwest Scotland, there are numerous traces of tide mills, including late examples [45].

*France*

Brittany alone boasted 90 of the 150 mills once found in France. The Rance estuary (Ile-et-Vilaine), on the northern coast, with 17 mills [46] and the Gulf of Morbihan, on the south coast, with 19 mills, are the two areas with the highest density. The remainder dotted the coast on the estuaries of small rivers such as the Jaudy and the Trieux (Côtes d'Armor), the Odet (Finistère), the Laïta, the Blavet and the Etel (Morbihan), at the head of small bays such as those of Fresnaye, Ploumanac'h (Côtes d'Armor) or the Rade de Brest. Others were built on the coast and there is still a mill on the island of Bréhat (Côtes d'Armor). In the Guerande basin (Loire-Atlantique) two or three mills were already reported derelict in the 14th century, while in the Mesquer basin, to the North, five mills operated in the 17th century. There was also a later, industrial, mill at Le Pouliguen, to the South.

On the Normandy coast, three or four mills have been documented: at the mouth of the Seulles at Courseulles-sur-Mer (Calvados), at Veules-les-Roses along the coast of the Pays de Caux (Seine-Maritime). Others undoubtedly existed in the Bay of Mont Saint Michel, since Richard I granted a building permit to the monks, near Carentan on the Vire, Caen on the mouth of the Orne and at Dieppe (Seine Maritime). The only known mill to the North of this area is the Dunkerque (Dunkirk) mill, described by Forest de Bélidor in the

1730's some twenty years after it had been abandoned. South of the Loire and up to the Spanish border, some 40 mills have been reported. Their distribution is very uneven: between 25 and 30 mills along the coast of Charente-Maritime and about a dozen in the French Basque Country. The Landes, with some 200 km of straight, sandy coastline do not offer the necessary conditions for the implantation of tide mills. A jagged coastline such as that of Brittany, with strong tides, offers the perfect setting, while the estuaries of Charente-Maritime are also very favorable. Thus, several mills were situated within the fortifications of the port of La Rochelle. Along the coast, the highest concentration, with eight mills, was to be found on the estuary of the Seudre, South of Rochefort-en-Mer, in the neighbourhood of the small town of Marennes [47]. A similar number of mills, eight or nine, was built on the Isle de Ré [48], opposite La Rochelle. Mills have been documented at Monards and St-Servin-d'Uzet, but it seems very likely that more existed in the estuary of the Gironde. The only known mill between the Gironde and the Basque Country, is that of Cir, between Arès and Andernos. This dual-powered mill existed till the late 18th or early 19th century.

In the French Basque Country (Pyrénées-Atlantiques) most of the mills were established on the estuaries of the Nive and the Adour [49]. Indeed, two were built at the confluence of the two rivers. On the right bank of the Adour, in the St Esprit quarter of Bayonne, six mills were still functioning in the early 19th century. Several others are mentioned in Ascain, Sopite and St-Jean-de-Luz. In all, some 30 mills are believed to have existed in the area.

*Iberian Peninsula*

On the other side of the Pyrenees, in the Iberian Peninsula, some 250 mills were built from the Bay of Biscay to the Straits of Gibraltar, though research here is still incipient. Thus, in their remarkable work on tide mills Jean-Louis Boithias and Antoine de la Vernhe [50] quote no more than 24 mills for the whole of Spain, whereas this figure corresponds to the mills "errota txiki" of the Spanish Basque Country alone. Of these, thirteen are in the province of Guipuzcoa, five of them near San Sebastián (a.k.a. Donostia) [51], and the eleven others in the province of Vizcaya.

According to the study published by the architect, Luis Azurmendi [52], some fifteen mills functioned at a time in the region of Cantabria between the city of Santander and the border with the Basque Country. They were situated in the small rí as such as Castellano or Quejo and in the "Marismas" or wetlands bordering them (e.g. de Joyel-Noja-Isla, de la Victoria) as well as in the Ría de Santoña at Escalante.

In the neighbouring Principality of Asturias, research is still very limited and the number of mills and their present condition is not known; nor has the documentary or bibliographic research that would allow to trace their distribution and significance been carried out [53]. Tide mills were to be found in the municipal districts or "concejos" of Llanes, Ribadesella, Villaviciosa, Gozón, Avilés, Navia and Castropol. In some instances the building still stands, in others only ruins remain, as is often the case in the United Kingdom. Unfortunately, in all the cases documented by A. Graña García and J. López Alvarez, the mechanisms have been dismantled. Often all that survives is a significant toponym (As Acias, Las Aceñas, La Enceña or La Enciena) indicating the erstwhile presence of a tide mill. In Asturias these names refer only to tide mills, and not, as is usually the case in the rest of the Iberian Peninsula, to water mills with a vertical wheel and horizontal axis. The same is true for Galicia, though here "aceña" and "aceas" are applied to both types of mill [54] (Fig. 1).

In the Northwest corner of Spain, Galicia, with its indented coastline also had a con-

siderable number of mills. The deep wide rías along the western coast, especially those of Muros (e.g. Muros de San Pedro), Noya, Arousa, Pontevedra and Vigo are ideal for the harnessing of tidal power. The highest concentration of mills was to be found in the Ría de Arousa (Seca in Cambados, As Aceñas on the Illa-island-de Arousa, and the Moiño do Cura) [55], in Catoira on the estuary of the Ulla. Aceñas de Xubia in the Ría de Ferrol and the Moiño das Mareas in Muros on the west bank of the Ría de Muros y Noia should also be mentioned. On the northern, Cantabrian and Galicia coasts, the smaller rí as of Betanzos, La Coruña, Lage and Camariñas are also good potential sites where several mills were built.

As elsewhere, the condition of Galician mills varies considerably from one site to another. Some times the buildings and mechanisms are fairly well preserved, in others all that remains is a significant toponym or documentary evidence. As far as Aceñas de Burgo, in the Ría do Burgo is concerned, only 16th and 18th century documents can vouch for the existence of this early mill which by 1580 already required repairs [56].

South of Galicia, in Portugal, numerous mills [57] are recorded, from North to South, in the estuaries which bite into the coastline. They are found on the estuaries of the Minho at Vianna do Castello and of the Douro at Salir do Porto in Caldas da Rainha (Norte), on the estuary of the Vouga and the Ría de Aveiro on the estuaries of the Mondego at Figueira da Foz (Centro), of the Tagus at Lisbon and Seixal, and of the Sado at Setubal and Alcácer do Sal. The highest concentration of all the European coastlines corresponds to the Tagus estuary where in the 18th century about one hundred mills were at work, mostly on the South bank opposite Lisbon, at the mouth of small tidal creeks flowing into the Mar da Palha (the inner estuary of the Tagus), between Alcohete and Seixal [58]. Two mills were situated at the mouth of the Mira at Vila Nova de Molfontes (Fig. 1).

The last major area of the Iberian Peninsula, with some 70 mills, is the littoral of the Gulf of Cadiz, between Cape St Vincent and the entrance to the Straits of Gibraltar, especially between Faro (Portugal) and the South of the Bay of Cadiz (Spain). In the western Algarve there were mills near Lagos and at Portimao, at the mouth of the Ribeira, but most of them were built in the eastern Algarve, between Faro and the mouth of the Guadiana, where 29 mills have been recorded [59]. Four mills were situated to the East, in the proximity of the town of Faro (esteiro do Minhos and Marinha da Garganta) and others at Olhao, Tavira and Castro Marim on the right bank of the former mouth of the Guadiana.

On the Spanish side of the border all the mills are located in the wetlands formed by the natural regularisation through history of the coast. Four mills functioned to the southeast of the fishing port of Ayamonte in the marshes bordering the mouth of the Guadiana. On the coast of the province of Huelva three further mills were built in the Marismas of the Piedras River and twelve others in the estuaries of the Tinto and Odiel rivers [60]. In the upper sector of the Tinto estuary seven mills were mapped in 1870. Although no mill is now known in the largest wetland in the Iberian Peninsula, the Marismas del Guadalquivir, there are indications that these once existed. The toponym El Molinillo, on the border of the former mediaeval banks of the Guadalquivir estuary, at La Algaida, Sanlúcar de Barrameda, and the Molino de Alventus, shown on an early map, in the municipal district of Trebujena also point to the presence of mills here. The last area in the Gulf of Cadiz with a high concentration of mills is the Bay of Cadiz, where seventeen mills have been located [61]. Seven of these are on the periphery of the Isla de León (San Fernando) and six others along the inner limit of the bay at Chiclana de la Frontera and Puerto Real.

There is no doubt whatsoever of their association with the salt pans which, at 6000 ha (28,800 acres), were the largest in Europe. The southernmost of the European Atlantic mills was to be found in the Barbate marshes within the confines of the Straits of Gibraltar where the tidal range is already limited.

*Elsewhere*

As far as other European countries are concerned, there were some twenty mills in The Netherlands, especially on what is today the large island of Zuid-Beveland (near Goes in Zeeland and in Flushings-Vlissingen) in the cities themselves [62]. These have not been in use since the 16–17th centuries. In Belgium, as already mentioned, two mills were established on the Rupel and the Scheldt rivers. It would undoubtedly be interesting to research the Atlantic coast of Morocco where the existence at one time of mills seems highly probable.

*The American Continent*

On the other side of the Atlantic some estimated 300 to 350 mills were built on the coastal stretch between Canada and Georgia (U.S.A.). Almost half the American mills, 150 to be precise, existed in Maine and Massachusetts (U.S.A.).

As stated, the first North American mill was built by the French, with the help of Micmac Indians, in Acadia (Canada) in 1613. The earliest tide mill to operate in the United States was the Salem Mill in Massachusetts, built in 1635, though there are some who claim that such a mill was already at work in 1617. Dutch colonists were among the first to build such mills in the United States, notably near New York, in the first half of the 17th century. Of these, the Spring Creek Mill still operated in 1899. Indeed, several mills were still working in New York State at the turn of the century, notably on Long Island at Garrettson's Creek, near Canarsie, and on Spring Creek [63]. Of the many mills built on the shores and in the coves of the island in the 18th and early 19th century the most imposing was undoubtedly the Van Wyck-Lefferts Mill mentioned earlier. In Passamaquoddy Bay at least two grist mills existed before 1800. The Brooklyn Mill, built after plans by the Italian Veranzio, is one of the few still standing. Indeed, today, not even ten mills in more or less good condition are to be found along the Atlantic seaboard of the United States [64]. On the tropical shores of the Caribbean several mills have been recorded, notably in Surinam (formerly Dutch Guyana) and others undoubtedly existed both in the Lesser and in the Greater Antilles, where they were used for sugar cane grinding [65].

Very little is known of the use of tidal energy on the Pacific coast except for an electrical motor which according to the Revue Scientifique (1902) was built in 1898 by the City of Santa Cruz (California).

*Distribution factors*

Several factors explain, to a certain extent, the geographic distribution of tide mills along the Atlantic littoral. These factors are linked to marine hydrology, the configuration of the coasts and the development of ports. A sufficient tidal range, at least two metres (6.5 ft), is the condition *sine qua non* for such a mill to function. As is to be expected, there is usually a high concentration of mills in areas with a considerable tidal range, as in the Rance estuary where it can go up to 13.25 m (43.7 ft), the West coast of Scotland (8 m; 26 ft) or other parts of the Breton Coast (5 to 10 m; 16.5 to 33 ft). The world's strongest tidal amplitudes, as much as 16 m (53 ft), are encountered in the Bay of Fundy (U.S.A.) in which the Memramcook and Petitcodiac rivers debouch. Passamaquoddy Bay, at 15 m (49 ft), or

the Bay of Saint Michel (France) where tidal range can reach 15.5 m (51 ft) are other excellent potential sites for the harnessing of tidal energy.

Nevertheless, tidal range does not appear to be a determining factor. In Spain and Portugal there are high concentrations of tide mills despite a limited tidal range which does not exceed, four metres ($\pm$12 ft) for the northern Cantabrian coast and a mere three to four metres for the rest of the peninsula during an average equinoctial spring tide. Indeed, in the Gulf of Cadiz, both in the Algarve and in Andalousia, the range is often below 3.5 m ($\pm$10.5 ft). Along the North Sea littoral, site of some of the earliest European mills or in Guyana, in the Caribbean, the range is under three metres (10 ft).

A mill also needs an indented coastline with inlets and small estuaries which can easily be blocked off by a causeway or marshes drained by numerous channels. This means that rectilinear coastlines, whether rocky or alluvial, even if the tidal range is favourable, are not ideal places for the implantation of tidal mills (e.g. the coast of the Landes in France). In fact most mills are to be found in estuaries or rías, on tidal channels, or within bays, as is the case of those built along the "barthes" (river estuaries at the bottom of a bay) of the French Basque country. Others, though fewer in number, are found on islands or peninsulas on rocky coasts or on the beach itself, where they occupy a sheltered position in relation to the flow and the strong tidal currents.

In southern Brittany numerous mills were built in the salt pans where they occasionally served to empty the reservoirs and ponds. Situated at the entrance to tidal creeks and the channels taking water to the pans the periodic emptying-out process served to clear away the deposits accumulated by the tidal flow, thus maintaining the depth of these channels. This is the case of the mills on the Isle de Ré and along the Charentais coast (France), the Ría de Aveiro, the Sado estuary and the Ría Formosa in Portugal, or the estuary of the Guadiana, the Ría de Huelva and the Bay of Cadiz in Spain.

The siting of mills is also conditioned by non-physical factors, mostly related to port development. Numerous mills clustered round historic port cities such as London [66], Southampton, Plymouth, La Rochelle, Bayonne, Lisbon, Faro or Cadiz. Strategic and commercial reasons, linked to supplying the population as well as the Navy, to the import and export of grains and flour led to their implantation within or close to the major ports. In certain cases there were also technical factors. La Rochelle is a case in point. Here the mills were used to clean the port using a complex system of sluices which allowed the silt to be evacuated with the outflowing water at low tide. The case of salt pans, mentioned above, is similar.

Changes in the natural environment may also lead to a mill having to be abandoned. A mill may no longer be able to function as a result of significant changes in littoral environment due to natural causes such as sedimentation or anthropic ones (drying out of marshes, filling in, etc.) [67]. The tide is then insufficient to fill the pond. When this occurs, the abandoned tide mill is evidence of a changing coastal landscape [68]. In some cases, such mills could be dual powered during an interim phase, prior to their total abandon.

## 4. MILLS AND THEIR ENVIRONMENT

This analysis concerns tide mills proper, *viz.* those mills whose machinery is moved solely by tidal power and, to a lesser extent, dual-powered mills. The latter depend on water from the river as well as on the tide and allow sea water to enter at low water so as to keep turning the wheels. Several such mills dot the Atlantic coasts. There are also double-effect

mills, i.e. mills which use both the incoming and the outgoing tides [69]. On the Thames, 6 m ($\pm$ 18 ft) water wheels installed under the arches of London Bridge, provided part of the city's water supply from 1682 to 1849. These wheels ran in either direction generating power with flood and ebb tides. This was also true of the East Greenwich Mill [70]. The famous French enamel artist, Bernard Palissy (1510–1589) refers to a double-effect mill which was probably to be found in Charente-Maritime. These mills followed the principles established by Captain Perse for the Dunkirk Mill [71].

Although the only properly documented Breton mill was that of Ludré, other mills in the Rance and in the Gulf of Morbihan could have functioned according to this principle and Azurmendi refers to the Boo mill in Galicia [72]. Water mills, even if they are on the coast, have been excluded from this review, as have the various aspects concerning milling techniques since these are not specific to tide mills.

*Mill and tide*

A tide mill is part of a unit which includes the mill itself, outbuildings, a dyke and a pond. The workings of a classic mill are simple. At high tide sea water flows into a pond, protected by a dyke, through a sluice gate which closes automatically, under pressure from the water accumulated in the pond, as the tide begins to withdraw. The water flows out of the pond through one or several narrower gates and, in so doing, turns the hydraulic wheels, which may be overshot, undershot or midshot.

The energy provided by tides, though intermittent, is regular and inexhaustible because constantly renewed. A mill functions from three hours before to three hours after low tide. Since wind can influence the speed of the incoming tide there could be marginal differences in the times, but these rarely varied by more than half an hour each way. Thus, the miller, who had to wait for the ebb tide before he could set his grinding stones in motion, had to adapt his working hours to the rhythm of the cycles of the tide, though on average he could expect to work a total of 12.4 h in every 24 h. The mill could not be used at all during neap tides, when tidal range is limited; a coefficient of at least 65 to 70 is required.

There are numerous variations on the pattern described above, according to the different geographical regions and we shall further try to summarise these.

*Dykes*

Dykes are built along a single continuous line, which may be straight or curved depending on the nature of the coastline and the degree of exposure. Their length varies considerably, though usually it ranges from 100 to 250 m (340 to 800 ft). In Brittany, the average length is 195 m (640 ft) in the Rance estuary and 145 m (490 ft) in the Gulf of Morbihan [73]. They can also be considerably longer (e.g. 300 m (990 ft) for the Joyel and La Victoria mills in Cantabria [74] (N. Spain) and 450 m (1449 ft) for La Beuzais in Brittany) or shorter (e.g. 70 m (230 ft) for the Traou-Mer mill (Côtes d'Armor), 90 m (295 ft) for that of Pencastel (Morbihan) and 51 m and 53 m (168 and 174 ft), respectively, for the mills of A Seca [75] and Do Cura [76] in Galicia (N. W. Spain)). They may also be built in sections taking advantage of rocky alignments and pebble spits forming part of a natural dyke. Two island mills, Birlo on the Ile de Bréhat in Brittany and another on the Illa de Arousa in Galicia have such dykes.

Variations in width are also considerable, though three to five metres is about average. The width of a dyke depends on the resistance to be opposed to the sea, the strength of the tides as well as on the shape of the dyke itself and the methods used in its construction.

The causeway of the Cosquer Mill (Finistère, Brittany) is 18 to 23 m (58 to 75 ft) wide! At the other extreme are some of the Galician dykes which can be no more than a metre (3.3 ft) wide. Often, the dyke is simply an earth levée protected by dry stone walls. In some cases the dyke is a thick wall strengthened by buttresses. Periodic de-silting of the pond allows the miller to raise or widen the dyke using the silt removed. The silting problem affects today many of the small Chinese tidal power plants.

*Entrance sluice gates*

In the dykes there are one or more openings formed by automatic, hinged gates through which sea water flows in at high tide. These "entrance" gates, usually three to four metres (10 to 13 ft) wide, may be found close to the mill or several dozen metres (40 ft) away from it, depending on the mill's position on the dyke. Occasionally, they are right under the mill as, for example, happens in the Coina mill in Barreiro (Galicia) or the Molino del Arillo in the Bay of Cadiz. The latter is also unusual in that its entrance sluices are placed perpendicular to the two wings of the building with a double gate under the central section of the main wing.

Sometimes they are divided into two or three sluices or water-gates separated by solid, stone, internal dividing-walls. In Cantabria [77] and in Galicia [78] most mills are equipped with double gates. The separating wall looks rather like a ship's prow stretching into the sea, which facilitates the flow of water into the pond at high tide. Contrary to Brittany, where there is usually only one entrance gate per mill, Spanish and Portuguese mills often have several. In Galicia, Begoña Bas López quotes five gates for the mills of A Seca and Mareas while in Andalousia the record is held by the Arillo Mill with seven.

The gates fixed to these sluices, called "gates to the sea" (*portes de la mer*) in France, are of two types and move either on a horizontal or a vertical axis. The former appear to be more frequent on the southern European coasts, though the Eling (U.K.) tide mill [79], constructed on a toll bridge, had flap valves. In the latter, i.e. the gates moving on a vertical axis rather like shutters, a stone fixed to the inner wall of the dyke limits the aperture to an angle of 90°. There are also combinations of sluice gates which are both automatic and manual [80]. In such cases the lower part is on a horizontal axis while the upper part is fixed and slides up and down between the uprights rather like a sash-window. When the sluices are fixed and sliding the mill is in fact a water mill which only rarely uses tidal power, otherwise it would require constant attention from the miller who would have to intervene with every changing tide.

*Ponds*

The size of ponds varies considerably since it depends on the coastline, the position of the dyke and on the tidal range. In Brittany, on the whole, ponds are larger in the South (8 ha (40 acres) in the Gulf of Morbihan) where the tidal range is more limited than in the North (2.9 ha; 14 acres) where the tidal range is greater [81]. The volume of water stored determines the mill's energy capacity and the number of hydraulic wheels that can be activated. In 1826, engineers recommended that the pond of the Herrera mill (Bay of Cadiz) be enlarged so as to increase the number of grinding stones. In Brittany ponds range from 0.2 ha (0.96 acres) (Combrit Mill) to 30 ha (14.4 acres) (Ludré Mill). The size of the Noyalo mill pond (77 ha; 370 acres) in the Gulf of Morbihan is exceptional since this is a dual-powered mill. Indeed, while some mill ponds range from 1.5 to 2 ha ($\pm 7$ to 10 acres), some fifteen are 3 to 6 ha (14 to 30 acres) large and as many others go from 8 to 13 ha ($\pm 38$ to

62 acres). Unfortunately, few authors give much detail on the size of mill ponds. In Portugal we can cite the Moinho Velho dos Paulistas whose pond covers 7.27 ha (34 acres) [82].

Some mills have several communicating ponds which means a longer working time for the mill, about 15 h in all, as water flows from one pond to the next. In France the only known example is that of Pont-Canada (Côtes d'Armor), but several examples are to be found in Great Britain. The Bishopston and Falmouth mills, in Sussex and Cornwall respectively, have been carefully studied. In the Bishopston Mill, an external channel linked the second to the first pond. Water from streams flowing into the ponds can help to fill these, but will rarely suffice to turn the wheels [83].

*Exit gates*

The purpose of the exit gates in single effect mills is to direct water accumulated in the pond during the flood tide towards the hydraulic wheels during the ebb tide. Their number depends on how many wheels are to be turned, though there are never more than three or four in Northern Europe. The channels are as wide as the wheels: 0.5 m (1.6 ft) in Southern Brittany and one metre (3.3 ft) in the North.

Further south and throughout the Iberian Peninsula the narrow, funnel-shaped channels give greater force to the water falling on the horizontal wheels. Their number is usually greater than in Northern Europe and never less than three. In fact, in Spain, mills with six or more channels are common. In Cantabria, on the North coast, Santa Olaja has nine; Joyel and Castellanos have eight each. In the Bay of Cadiz, the San José Mill has eight channels. In Galicia (N.W. Spain) their number varies from three to six, with narrow channels being associated to wider ones [84].

*Wheels*

There is another significant difference between Northern and Southern European tide mills: while the former are generally equipped with vertical wheels, whether internal or external, the latter tend to have horizontal, internal wheels. A census carried out in Brittany in 1809 showed that 80% of the 6450 wheels were vertical, and only 20% horizontal [85], the latter being extremely rare in southern Brittany. While in Great Britain almost all vertical wheels are external, across the Channel, in Brittany, they may also be internal.

The number of wheels varies from one to three whether they be internal, external or a combination of the two, as is the case in the Pencastel Mill (Morbihan). They may be on the same course, parallel, off-course or placed one after the other. Waterwheels in tide mills were usually wooden, though some were spoked wheels with iron hubs. The wheel shafts, of wood and iron, also varied considerably in size.

The wheels of the Rhode Island Mill (U.S.A.) were eight metres (26.3 ft) wide, with a diameter of 3.35 m (11 ft) and weighed 20 tons [86]. In England, Stambridge Mill, on the river Roach, near Rochford, had a wheel 9.9 m (32.6 ft) wide with a diameter of approximately 5.5 m (18 ft). Mounted on a wooden shaft it drove three pairs of stones. The dual-powered (river-run and tide) mill at Demi-Ville (Morbihan) had wheels with a diameter of 5.6 m (18.5 ft). On the whole wheels tend to be narrower in the South than in the North.

The case of the Iberian Peninsula, and especially Spain, is rather different and mills tend to have a far greater number of wheels. The mills of La Venera (Cantabria) and El Arillo (Bay of Cadiz) had thirteen and twelve, respectively, though in 1828 engineers suggested equipping the latter with as many as 20 wheels [87] (Fig. 10). Each of these wheels is placed at the bottom of a kind of individual cylindrical stone well at the base of which there is a

wooden beam into which the shaft is inserted. It is the shaft which transmits power to the grinding stones.

These horizontal wheels are of two types: "a rodicio" and "a rodete". The former, or "ruedas a rodicio", are older and have curved paddles. Their diameter varies from 0.9 m for the Fontas Mill in Lagos to 1.5 m (5 ft) in the A Mouriscas Mill on the Sado estuary (Portugal). The wheels of the A Mouriscas Mill, with their 22 curved paddles, can reach speeds of 150 r.p.m. [88]. The "rueda a rodete" does not have paddles, but a smooth external surface and straight, solid wood spokes. In many cases this newer type of wheel replaced paddled wheels since, being placed lower on the supporting beam, it prolonged the working time of a mill.

*The mill*

The mill itself may be built in the middle or at either end of the dyke, the exact place being usually determined by the topography and/or hydrology. Industrial mills, however, are usually built at one end of the causeway as this offers easier access.

The architecture of tide mills is only skimmed over since it is largely comparable to that of water mills. As mentioned, from the mid-nineteenth century industrial mills could have three, four and even five storeys. The floor plan can be up to three times larger than that of the traditional mills they often replaced (e.g. Rochegoude Mill, from 8.3 m $\times$ 10 m to 13 $\times$ 20.5 m (27.4 $\times$ 33 $\times$ 43 $\times$ 67.6 ft) [89]. These traditional mills show considerable variation in size. Most of them are of a more or less pronounced rectangular shape (e.g. in Galicia, 9 $\times$ 13.7 m (29.5 $\times$ 45 ft) for the De Cura Mill, 6.2 $\times$ 20.5 m (20 $\times$ 67.6 ft) for the Acea da Ma Mill) [90]. Although most are one or two storeys buildings, in the South a third floor may be added for the miller's dwelling. From the 19th century, in Brittany, the miller's dwelling tends to be built away from the mill proper.

In mills equipped with horizontal internal wheels, the cavity under the building is reserved for these and for the mechanisms transmitting power to the grinding stones in all cases. When wheels are vertical, this cavity is virtually empty (e.g. Rance estuary).

In his work on the mills of Brittany, Jean-Louis Boithias [91] has identified several architectural types:

(a) the upper part containing the grinding wheels is a light wooden structure, built on piles above solid stone foundations (e.g. Vauban in Paimpol, Lupin in the cove of Rotheneuf);
(b) the side walls are left open and blocked in with wooden planks (e.g. Traou-Meur, Grand Traouéiros, in Côtes d'Armor);
(c) in simple masonry (e.g. Birlo, Dourduff-en-Terre).

Buttresses, whether on the front or sides, sometimes reinforce the walls providing stability and greater resistance to storms which can be frequent in the area, and act as breakwaters.

Mills situated South of Brittany, from the coast of Charente-Maritime all the way to the Bay of Cadiz going through the Basque Country, Galicia, and the various Portuguese regions, all presented the same aspect on the sea-facing facade: a succession of arches which, when their number is high, gives the mill the appearance of a covered bridge. There are fewer arches than there are exit sluices or hydraulic wheels. Thus, in Cantabria, the Santa Olaja mill has seven arches to nine wheels, that of La Victoria three arches to eight wheels and La Venera six arches to thirteen wheels [92].

In Portugal and in the Gulf of Cadiz mills are often of a considerable size and together

with their numerous outbuildings frequently constitute veritable complexes. Indeed, some mills had their own chapel. Huge pottery urns were used for storing fresh water (e.g. San José Mill, Bay of Cadiz) [93]. Above the machinery and the grinding stones there were grain stores. In the upper part of the mill, whether in the area reserved for milling or in the store rooms above, most mills had a door through which the sacks of flour could be loaded directly on to boats at high tide.

On the whole tide mills were used for grinding grains (wheat, barley, rye and, in Brittany, buckwheat) and complemented wind mills [94]. Between 1823 and 1828 the Cadiz mills ground grain to feed the French occupation forces.

Tide mills were also put to other uses. As already mentioned the mill on London Bridge provided fresh water for the City up to the late 19th century. Bidston, in Cheshire, was an iron-slitting mill and some mills were used for rasping and chipping dyeing woods and the manufacture of tobacco stems. Some mills were providing power for breweries. The copper smelting works established in the Hayle Mill in Cornwall in the mid-eighteenth century were eventually abandoned as no one could be found to work when the tides provided power at different times of day and night. Slade's Spice Mill, in Chelsea, Massachusetts, was used, as its name indicates, for the grinding of spices. The two tide mills operating in Passamaquoddy Bay prior to 1800, however, were standard grist mills.

In Trégor (Brittany) several early mills were transformed and used for flax. In the Spanish Basque Country, the Mallukisa mill in Murrieta (Province of Vizcaya) was used to grind kaolin which was then sold to the San Mamés porcelain factory. Some mills situated within salt pans were used for washing salt as was the case of the Loix Mill (Ile de Ré, France) in 1824–1825, while others were converted to paper mills, saw mills and carpenters' workshops and even used for the manufacture of ice. Still other mills were used in drying up of polder (Netherlands).

## 5. THE PROTECTION OF A RARE HERITAGE

After they stopped grinding wheat and other grains most of the mills were either abandoned or simply pulled down. All too often their environment (dykes, ponds) was also significantly altered.

Many mills, having lost their roofs, rapidly became derelict thus increasing the threat of total obliteration. In some cases the walls were raised to just above ground level, in others the destruction was total. They have served as quarries for the building of houses, as is the case at Dourduff-sur-Mer (Finistère, France) or made room for villas (Aceñas de Knead, Galicia) [95] or even for Council flats (HLM ; habitations à loyer modeste) as happened in Pouliguen (Loire-Atlantique, France) in 1972 [96].

Their original architecture can also be affected by the addition of cement, concrete blocks, aluminium doors and windows or the presence of modern buildings next to them. Examples of this kind of architectural vandalism are numerous from the United Kingdom to southern Spain.

Mill dykes, when not partly or totally destroyed, have been cemented, raised or widened in order to make way for new roads. They can also serve for the construction of houses as in As Aceñas de Verxeles (Galicia) which was sold to two different people in 1951, each of whom proceeded to build his own villa. The deed drawn up on the occasion gives a good description of the mill as it was at the time [97].

The most serious problems are due to the deterioration of mill ponds. Since they are no

longer filled and emptied with every tide, they have a tendency to naturally silt up. Silt and vegetation soon invade a large sector of their surface area. This natural trend, resulting from the fact that the pond is no longer cleared with ebb tide as it was when the mill was functioning, is further aggravated when the ponds are cut by other dykes or roads (e.g. the Pomper Mill in the Golfe du Morbihan). Man is also responsible for the drying up or filling-in of several ponds for agricultural purposes or to turn them into building land. In Cantabria pressure from developers is very strong indeed. In Huelva, it is industrial waste (calcium phosphates, etc.) that covers the surface of several former mill-ponds on the right bank of the Tinto estuary [98].

Ponds are often also used as fresh water reservoirs. Nevertheless, the most frequent use is for aquaculture as happens in Brittany and Cantabria.

In Morbihan (France) some former millers have turned to oyster farming, using their mill ponds for the breeding of oysters. In the same French department there are plans to create several oyster nurseries in such structures. This is, on the whole, positive, as it helps to maintain the pond's physiognomy, but can become a threat when it is a question of developing aquaculture without taking into account existing structures, as has happened in several parts of the Iberian peninsula (Bay of Cadiz).

Finally, we should stress a contradiction: the installation of the first tidal power station in the world, at the mouth of the Rance (Brittany, France) in 1966, is the direct cause of the silting up of 17 mill ponds up stream on the estuary. This power station, with a production of 500 million Kw/h, has reduced the tidal range and the currents within the estuary.

A certain number of mills have been saved from destruction or total ruin by being converted into dwellings, antique shops, restaurants and other uses. This has favoured their conservation and the restoration work is often of the highest quality. In Brittany there are the examples of Rochegaude or Buguélès on the northern coast and Coët-Courzo, Le Bono, Mériadec, Pomper, Hézo and Pencastel on the Gulf of Morbihan. Unfortunately, such conversions often lead to the total disappearance of the inner machinery of the mills, while the hydraulic wheels fall into disuse and gradually rot.

Sometimes, by being restored or turned into museums they become tourist and cultural attractions. The Plougastel Mill nearly missed being turned into a restaurant. In Great Britain the Woodbridge tide mill (Suffolk) was restored between 1953 and 1970. The Eling Tide Mill Trust acquired the mill on Southampton water in 1975 and had it restored by 1980 when it became a working museum attracting large numbers of visitors [99]. The Beaulieu Mill was also restored and was in use in 1970. The Ruppelmonde Mill in East Flanders (Belgium) now houses a milling museum. Since 1979 Mr and Mrs Le Page have carefully restored the Traou-Meur Mill (Brittany), opening it to the public in 1989. In the same French department, the Petit Traouiéros Mill, bought by the municipal authorities of Perros-Guirec in 1964, houses a permanent exhibition on tide mills. There are also plans to restore the Birlot Mill, on the island of Bréhat.

In Finistère, the Hénan Mill (Névez) was bought by the department and carefully restored, and the Pont Mill has been turned into a museum on flax and linen. In Cantabria (N. Spain) the architect Luis Azurmendi [100] has drawn up plans for the restoration of La Venera Mill and for an eco-museum to be housed in the Joyel Mill. Another architect, Jesús Anaya, has drawn up a project for the Pozo de Cachón Mill in Muros de San Pedro (Galicia, N.W. Spain) which is to be financed by the European Council [101]. Plans here include clearing the sediment accumulated in the pond and the rebuilding of the dyke. The

buildings will be devoted to an eco-museum and a youth hostel. Unfortunately, all projects for the preservation of mills in the Bay of Cadiz have so far come to naught.

In Portugal, the Corroios Mill (Seixal, South bank of the Tagus), bought by the municipal authorities in 1986, is in perfect functioning order and has become an industrial heritage centre and eco-museum. There are similar plans for the Alcácer do Sal Mill on the Sado estuary, and the nearby A Mouriscas Mill, within the Reserva Natural do Estuário do Sado, is to become an information and interpretation centre for this Nature Reserve [102]. In North America, a replica of the Bay of Fundy Mill has been placed near the Annapolis-Royal power station.

Several other mills have been restored in Spain : at la Coruña a tide mill has been restored and accomodates also an ecomuseum and a hostel. In Cantabria, at Bareyo the "Venera" Mill has been also restored, and so has the mill on the rio Arillo (Cadiz area). The Council of Europe is helping with the restoration of a mill in Galicia.

In Great Britain the Woodbridge tide mill, an 18th century clapboard-mill, has been completely restored and functions during the summer. Rex Wailes (*op. cit.*) holds that this mill, on the Deben estuary (Suffolk) dates from 1170. Reportedly it was still in use in 1961. Still older (1135), the Bromley-by-Bow Mill functioned during the entire second World War. Of three mills nearby, dating from the 12th century, the Clock Mill, rebuilt in 1817, is best known.

The Eling tide mill, located on the Southampton Water, may well be one of the oldest in England ; indeed two corn mills are mentioned in the 1086 Domesday Survey. If, as possible, they were—or one was tide-powered—it has worked them for at least 911 years. The mill has been repeatedly the subject of historical recording ; the present building was probably erected in 1785. Threatened economically before World War I, the demands of the war

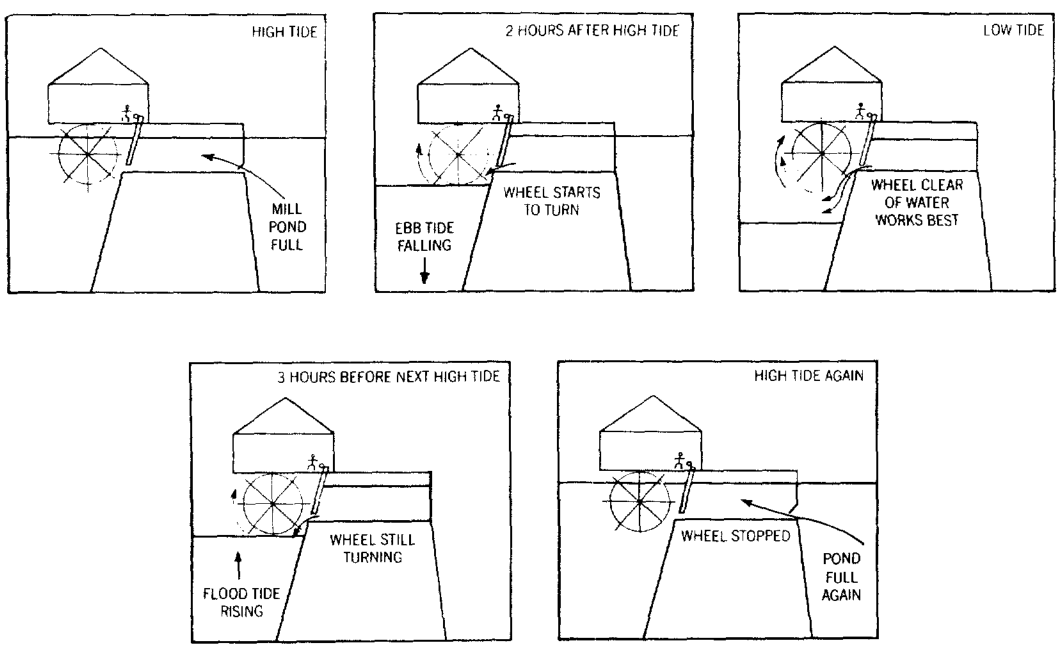


Fig. 11. How a tide mill functioned. (Source : Southgate.)

years provided a reprieve. Eling Mill, though faced by steam roller-mills competition, was better situated to stand up to the challenge, than inland water mills because of its own access to the sea [79]. Manned by World War II Italian war prisoners for a while, it stopped working in 1941. The Eling Tide Mill Trust acquired the mill in 1975 and had it restored by 1980, when it became a working museum (Fig. 12).

For 50 years, notwithstanding its small capacity, Eling stood up to competition because it concentrated on feedstuffs and on small orders from local farmers (Fig. 13) [79]. If it stopped working, it was less because of economics than because the mill, diesel-powered since 1936, did not meet new regulations on food production.

The mill was an example of "double-mills" where two separate water-wheels each independently had a set of machinery. Another "characteristic" is that it is a tide mill unicum as it regularly produces wholemeal flour and achieved the longest milling time (15 h 25 min) in a day (*Guinness Book of Records* 1987).

In Southampton some records mention that the town ditch was regularly filled by the tide; a mill had been installed in a massive stone barbicane to command the moat at the seaward corner of the walls. Margaret Deacon, of Southampton University, reported that the ancient mill had been restored and is fully operative, attracting, of course, impressive numbers of tourists since 1980. The Beaulieu Mill, in use in 1970, has also been restored.

*A technology of the past, or one with a new future?*

All these mills were of local importance with often the entire industry of the village centred upon the mill. The mechanical energy produced was modest, mostly for local use, ranging from 30 to 100 kW, a certain factor in their demise. Problems were compounded by the appearance of the electric motor, long distance transmission, and the advent of power economics.

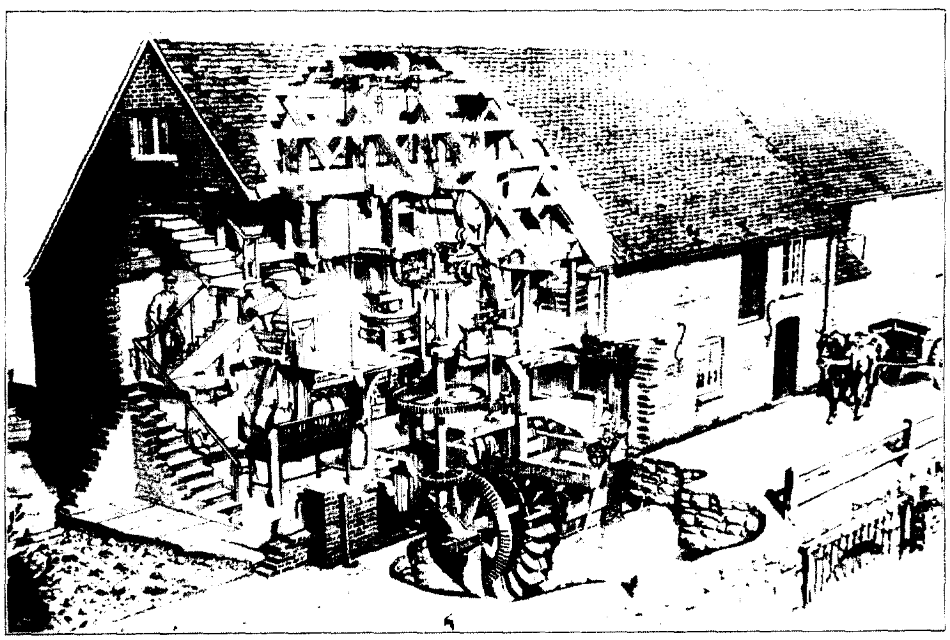

Fig. 12. Drawing by Mel Wright of Eling Mill "at work".

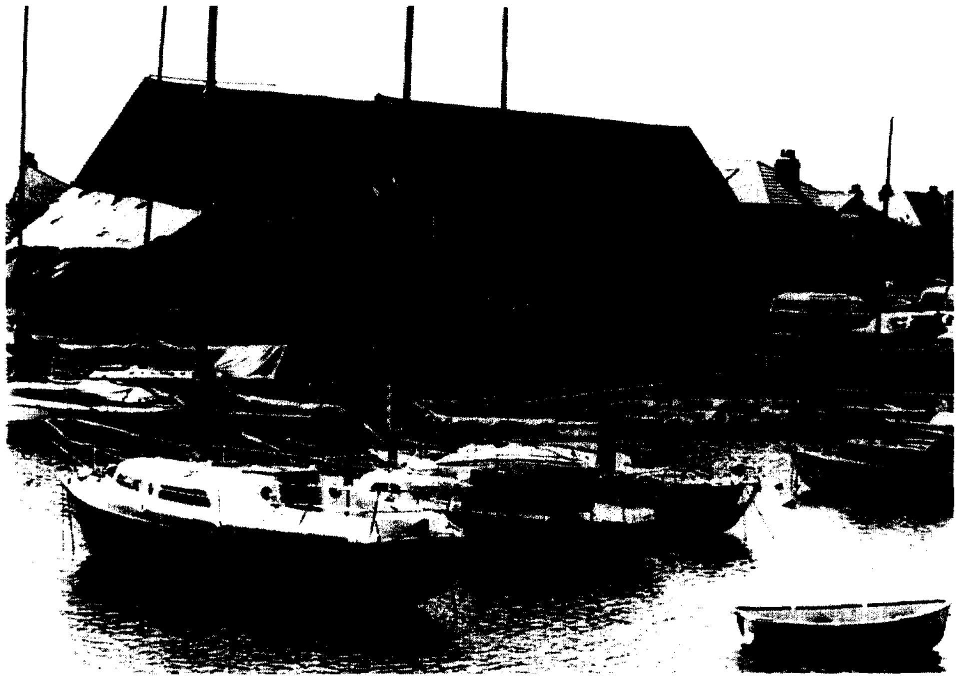

Fig. 13. Eling tide mill situated near Southampton. Restoration was completed in 1980 and the working museum currently produces stone-ground wholemeal flour. (Photo. David Plunkett).

Fig. 14. Traou-Meur (Côtes d'Armor, France) tide mill (17th century). View from sea. Notice, left, the trap door gate allowing entry of sea water to fill pond at rear of dike, and to the right, gate allowing water exit and pushing the two hydraulic wheels. (Photo. L. Ménanteau.)

Fig. 15. Grand Traouiéros dike and mill (14th century). Side and front buttresses insure construction stability and act as wave breakers during storms, Trégastel, Côtes d'Armor, France. (Photo. L. Ménanteau.)


Fig. 16. Early 20th century Uregna tide mill, on the Caño de Zaporito in San Fernando, Cadiz Bay, Spain, seen from sea. (Postcards coll. L. Ménanteau.)

Fig. 17. Arillo Mill (Cadiz, Spain). Central gates. (Photo. L. Ménanteau.)

Fig. 18. Chiclana de la Frontera (Cadiz Bay, Spain). Bartivas tide mill and its fully filled in basin. (Photo. L. Ménanteau.)

Fig. 19. Buttressed stone dyke of one of the two ponds of the industrial type mill of Pont Canada (late 19th century) on the estuary of the Jaudy (Trédarzec, Côtes d'Armor). In the background, the four storey mill which is now a marine supermarket (Co-per Marine). (Photo. Loïc Ménanteau (June 1993).)

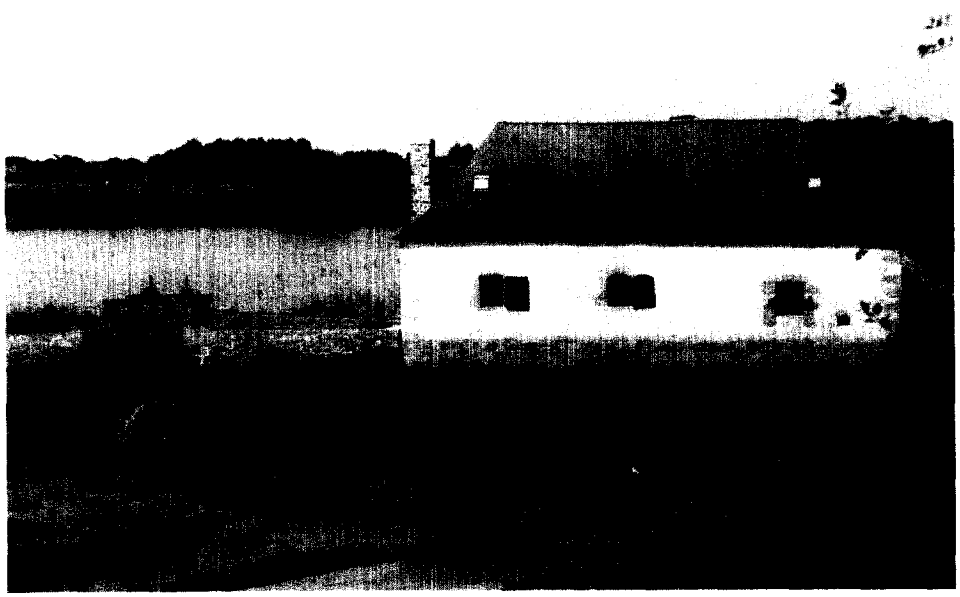

Fig. 20. Morbihan Gulf, France. Mériadec Mill at Baden, with its dike and two twinned-gates with trap door. (Photo. L. Ménanteau.)

Fig. 21. The Ancillo Mill (Marismas de Santoña, Cantabria, N. Spain) in the centre of the dyke with the pond in the background. The two arches on the left correspond to exit sluices which activated the mill horizontal wheels, while the larger arch on the right covers the entrance sluice which directed water to the pond at high tide. (Photo. Luis Azurmendi.)

Fig. 22. Remains of two paddle wheels from the Kervilio mill at Plougoumelen (Morbihan, France) aligned one after the other in the same channel which runs parallel to the mill building. (Photo. Loïc Ménanteau (June 1993).)

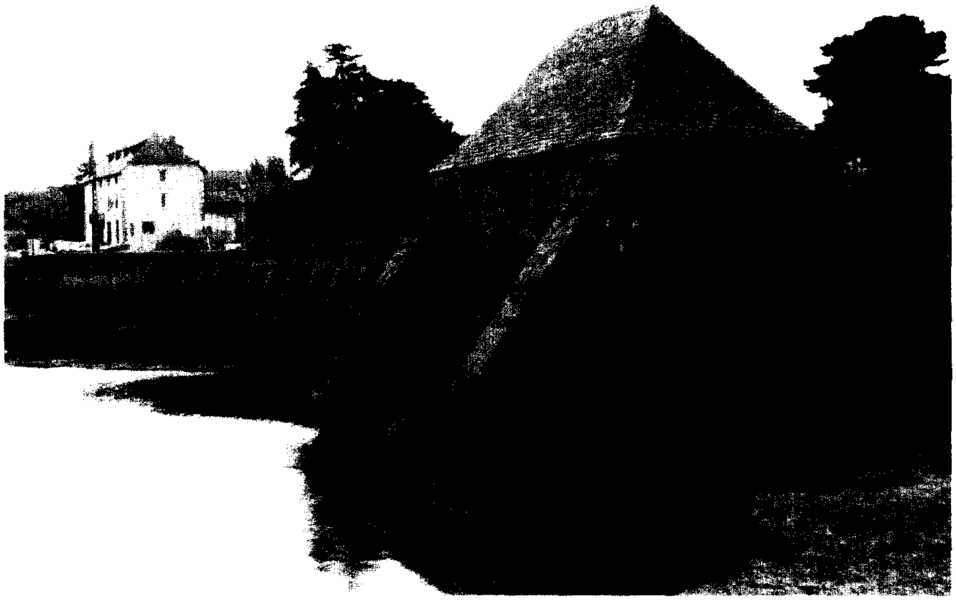

Fig. 23. The Pettit Traouiéros Mill (19th century) near Perros-Guirec, Côtes d'Armor, France, with a buttressed dike, seen from the sea in June 1993. (Photo. Loïc Ménanteau.)

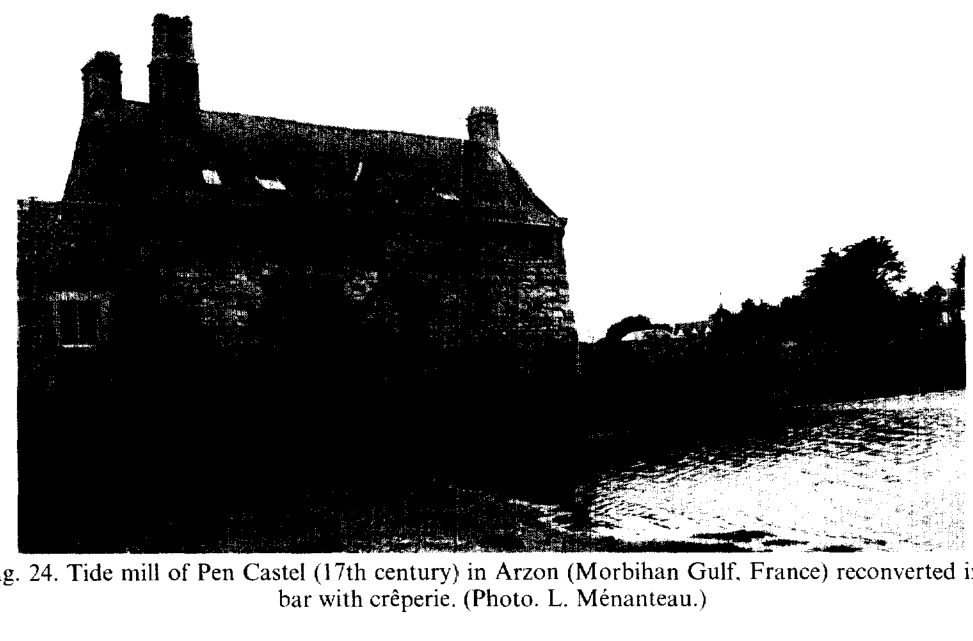

Fig. 24. Tide mill of Pen Castel (17th century) in Arzon (Morbihan Gulf, France) reconverted in a bar with crêperie. (Photo. L. Ménanteau.)

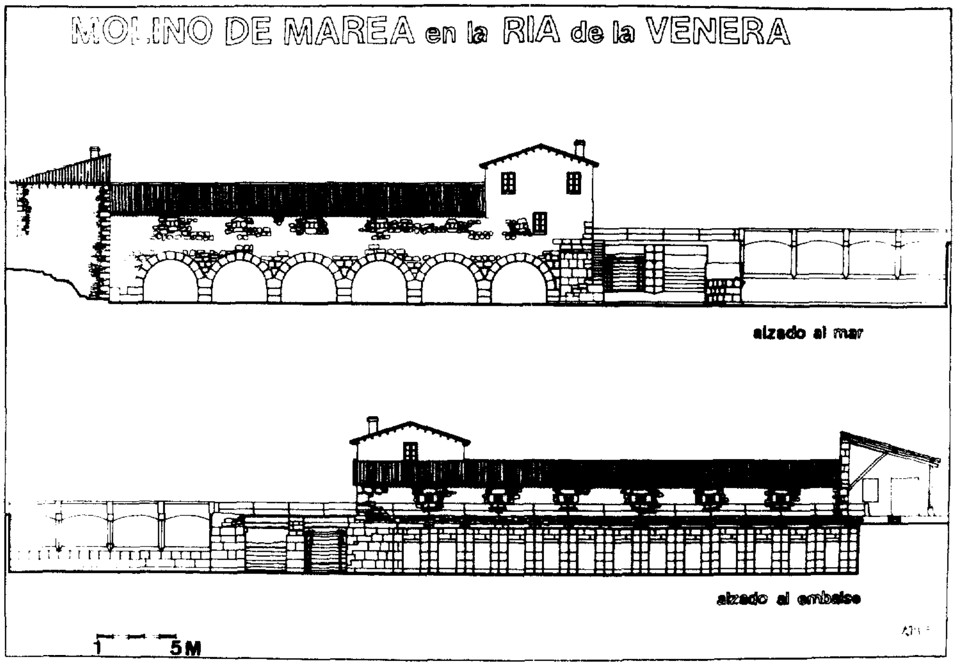

Fig. 25. Tide mill in the Ría of the Venera (Spain). Above towards the sea; below, landwards.

Tide mills tried with waterwheels, water pressurisation, air compression, lifted platforms to put to work the tides' potential energy, the tidal currents kinetic energy, or both. They died of technological obsolescence, losing the competition battle with lesser priced thermal and river plants. Their virtue is to not consume irreplaceable stores of energy and to be a continuously available source of energy. Their gradual disappearance is a loss; their restoration could perhaps refloat decaying village industries.

Popular interest for tide mills has steadily grown. The "rediscovered" old tide mill near Plougastel (Brittany) was restored instead of becoming a restaurant. New England also boasts a working tide mill in a nature preserve. Indeed, a new lease on life may have started for the tide mill in tourism, archaeology, small energy source, cottage or village industry power source.

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